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# Experimental and Theoretical Investigation of Electrochemical Machining Process

Suresh H. Surekar
Department of Production Engineering
KIT's College of Engineering
Kolhapur, India

Sudhir G. Bhatwadekar
Department of Production Engineering
KIT's College of Engineering
Kolhapur, India

***Abstract*— Electrochemical Machining (ECM) has proven to be very effective in machining difficult-to-cut materials because of high removal rates. It is a relatively new and important method of removing material from the surface or drilling the hole in workpiece and offers a number of advantages over other machining methods. Material removal from the workpiece is done by means of Principle of Electrolysis. It is an electrolytic process and its basis is the phenomenon of electrolysis, whose laws were established by Faraday. Metal removal is effected by a suitably shaped tool electrode, and the parts thus produced have the specified shape, dimensions, and surface finish. Experimentally material removal rate is calculated by measuring weight of the workpiece before and after machining. In theoretical material removal rate the process control parameters are not considered. Electrochemical drilling is affected by number of parameters such as tool feed rate, voltage, electrolyte flow rate, electrolyte concentration etc. Taguchi method of optimization is used for parameter combinations and to carry out experimentations to calculate material removal rate. The input parameters are termed as Signal and error in the response/result is termed as Noise (S/N). Workpiece used in the electrochemical machining process is Hastelloy C-276 (Ni-Base Superalloy) because of its high hardness and special applications such as aerospace chemical etc.**

***Keywords*— Electrochemical Machining Process, Material Removal Rate, Hasetlloy C-276, Taguchi Me***

## I. INTRODUCTION

Electrochemical Machining Process is a non-traditional, non- conventional, non-mechanical machining process in which material removal from the workpiece is done by means of Principle of Electrolysis [1-5]. It is an electrolytic process and its basis is the phenomenon of electrolysis, whose laws were established by Faraday in 1833. Electrolysis is the name given to the chemical process which occurs when an electric current is passed between two conductors dipped into a liquid solution. The system of electrodes and electrolyte is referred to as the electrolytic cell and the chemical reactions which occur at the electrodes are called the anodic or cathodic reactions or processes respectively.

The principle of electrochemical machining process is shown in fig.1. The process of electrochemical machining is developed on the principle of Faraday's law and Ohm's law. In this process an electrolytic cell is formed by the anode (work piece) and the cathode (tool) in the static or flowing electrolyte. The metal is removed by the controlled dissolution of the anode according to the well known Faraday's law of electrolysis when the electromotive force (*emf)* is applied across electrodes, flow of current in the electrolyte is established due to positively charged ions being attracted towards the cathode and negatively ions are attracted towards anode. Current/current density depends on the rate at which ions arrive at respective electrodes which are proportional to the applied voltage, concentration of electrolyte, the gap between the electrodes and tool feed rate.

The material removal rate (MRR) is affected by various parameters which are controllable as well as non-controllable. Metal removal is achieved by electrochemical dissolution of an anodically polarized workpiece which is one part of an electrolytic cell in ECM. Hard passive alloys, such as nickel-base superalloys (Hastelloy C-276) [6] are widely used in various industries, such as chemical, aircraft and automotive industries can be shaped electrolytically by using ECM and the rate of machining does not depend on their mechanical properties.

Electrochemical Machining is a relatively new and important method of removing material from the surface or drilling the hole in workpiece and offers a number of advantages over other machining methods (conventional / unconventional). Metal removal is effected by a suitably shaped tool electrode, and the parts thus produced have the specified shape, dimensions, and surface finish. Being a non-mechanical metal removal process, ECM is capable of machining any (high strength high temperature alloys) electrically conductive material with high stock removal rates regardless of their mechanical properties such as hardness. ECM is employed in many applications, for example, for automotive, offshore petroleum, and medical engineering industries, as well as by aerospace firms, which are its principal user. ECM leaves no burrs; one ECM operation can replace several operations of mechanical machining. Hard passive alloys are widely used in various industries, such as chemical, aircraft and automotive industries. Electrochemical Machining (ECM) has proven to be very effective in machining difficult-to-cut materials because of high removal rates, ability to generate complicated contours and profiles, no tool wear, no burrs and no scratches left on the machined surface. The passivation effect can negatively influences the productivity of the ECM process. Theoretically material removal rate is calculated by means of Faraday's laws.

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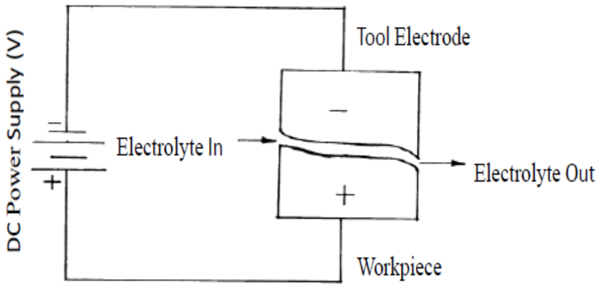


Fig.1: Principle of Electrochemical Machining

Experimentally material removal rate is calculated by measuring weight of the workpiece before and after machining Electrochemical drilling is affected by number of parameters such as tool feed rate, voltage, electrolyte flow rate, electrolyte concentration etc. Taguchi method of optimization is used for parameter combinations and to carry out experimentations to calculate material removal rate [7]. The input parameters are termed as Signal and error in the response/result is termed as Noise (S/N). Workpiece used in the electrochemical machining process is Hastelloy C-276 (Ni-Base Superalloy) because of its high hardness and special applications such as aerospace chemical etc.

## II. MATERIAL REMOVAL RATE (MRR)

Material removal rate (MRR) in ECM is calculated by means of Faraday's laws [8]. Faraday's laws state that: (1) the amount of chemical change produced by an electric current i.e. the amount of any material dissolved or deposited is proportional to the quantity of electricity passed. (2) The amount of different substances dissolved or deposited by the same quantity of electricity are proportional to their chemical equivalent weights. From faradays two laws,

Material Removed/Dissolved (M) α I x t x € (1)

$$M = \frac{I \, x \, t \, x \, €}{F} \quad (2)$$

Where, M – Mass of material dissolved, gm (gram)
I – current, A (ampere)
T – Time, hr (hour)
€ - gram equivalent weight
F – Faraday's constant, (A hr)

The gram equivalent weight of the metal is given by € = A/Z where A is atomic weight and Z is the valancy of the ions produced. Therefore

$$M = \frac{I \, x \, t \, x \, A}{ZF} \quad (3)$$

Equation (2) contains constant and variable parameters, in this current/voltage and valancy are variable and remaining all parameters are constant for single element. To calculate material removal rate for workpiece containing number of elements equation (3) is used.

$$MRR = \frac{I}{F\rho \sum_{i=1}^{n} \frac{X_i Z_i}{A_i}} \quad (4)$$

Where, I - Current (A)
F - Faraday's constant (26.8 A hr)
$\rho$ - Density of material, (8.89 g/cm$^3$)
A - Atomic weight of element
Z - Valancy of element
X - Percentage composition of element

The chemical composition of Hastelloy C-276 along with percentage and valancy and atomic weight is given in table 1. From table 1 it is clear that each element of the workpiece is having multiple valancies and valancy changes as temperature changes. Therefore temperature and pH of electrolyte is considered constant. To calculate material removal rate theoretically voltage has been taken as e.g. 12 V, 14 V and 16 V. From this voltage current required for calculation of MRR is calculated by considering material's and electrolyte's conductivity by means of Ohms law. While calculating MRR other process parameters are not taken into consideration. Accurate material removal rate has not been calculated theoretically as every element has multiple valancy (Z) and valancy changes as temperature changes. As well as the percentage of each element has been given in the range ant it is impossible to add exact percentage. Hence for calculating MRR values are taken as minimum (-1), intermediate (0) and maximum (+1). Taguchi methodology is used for parameter combinations at different levels as the parameter affecting MRR to the large extent is impossible to predict directly. Therefore L9 orthogonal array has been taken for parameter combinations at different levels. The L9 orthogonal array along with parameter values is given in the table 2.

TABLE 1: CHEMICAL PROPERTIES OF HASTELLOY C-276 [9, 10]

| S. N. | Name of Element | Percentage (X) | Valancy (Z) | Atomic weight (gm) |
|---|---|---|---|---|
| 1 | Nickel | 57 | 2,3 | 58.693 |
| 2 | Molybdenum | 15-17 | 3,4,6 | 95.96 |
| 3 | Chromium | 14.5-16.5 | 2,3,6 | 51.996 |
| 4 | Carbon | 0.01 | 1,2,4 | 12.011 |
| 5 | Manganese | 1.0 | 2,3,4,6,7 | 54.938 |
| 6 | Silicon | 0.08 | 2,3,4 | 28.085 |
| 7 | Iron | 4-7 | 2,3, | 55.845 |
| 8 | Tungsten | 3-4.5 | 6,8 | 183.54 |
| 9 | Cobalt | 2.5 | 2,3, | 58.933 |
| 10 | Vanadium | 0.35 | 3,5 | 50.94 |
| 11 | Phosphorous | 0.025 | 3,4 | 30.97 |
| 12 | Sulphur | 0.01 | 2,4,6 | 32.07 |

Experimentally material removal rate is calculated as a difference in weight i.e. weight before drilling/machining – weight after drilling/machining. To calculate material removal rate electronic weight balance is used with least count of 10 mg.

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TABLE 2:L9 ORTHOGONAL ARRAYS WITH THEORETICAL VALUES

| S.N. | Voltage | Percentage | valancy |
|---|---|---|---|
| 1 | 12 | -1 | -1 |
| 2 | 12 | 0 | 0 |
| 3 | 12 | 1 | 1 |
| 4 | 14 | -1 | 0 |
| 5 | 14 | 0 | 1 |
| 6 | 14 | 1 | -1 |
| 7 | 16 | -1 | 1 |
| 8 | 16 | 0 | -1 |
| 9 | 16 | 1 | 0 |

$$MRR = \frac{(Wb - Wa)}{T} \quad (5)$$

Where Wb : weight (gm) before machining/drilling
Wa : weight after machining/drilling
T : time of machining/ drilling

To calculate material removal rate experimentally only weight of the workpiece before after drilling or machining is considered. The process control parameters are not considered hence Taguchi method of optimization is used to carry out experimentations and to combine parameters at different levels. The parameters considered for experimentation are voltage, feed rate and electrolyte flow rate. L9 orthogonal array along with parameter combinations at different levels is given in table 3. To carry out experimentations a set developed and fabricated as shown in figure 2.

## III. RESULTS AND DISSCUSSION

Theoretical material removal rate is calculated by means of "(4)" and is given in table 3. From the table it is clear that large volume of material is removed at high voltage, intermediate percentage and minimum valancy as MRR is directly proportional to the voltage and inversely proportional to the valancy.

TABLE 3 THEORETICAL MATERIAL REMOVAL RATE

| S.N. | Voltage | Percentage | valancy | MRR $x10^{-6}$ $mm^3/min$ |
|---|---|---|---|---|
| 1 | 12 | -1 | -1 | 1.66 |
| 2 | 12 | 0 | 0 | 1.49 |
| 3 | 12 | 1 | 1 | 1.45 |
| 4 | 14 | -1 | 0 | 1.79 |
| 5 | 14 | 0 | 1 | 1.68 |
| 6 | 14 | 1 | -1 | 1.87 |
| 7 | 16 | -1 | 1 | 1.97 |
| **8** | **16** | **0** | **-1** | **2.12** |
| 9 | 16 | 1 | 0 | 2.00 |

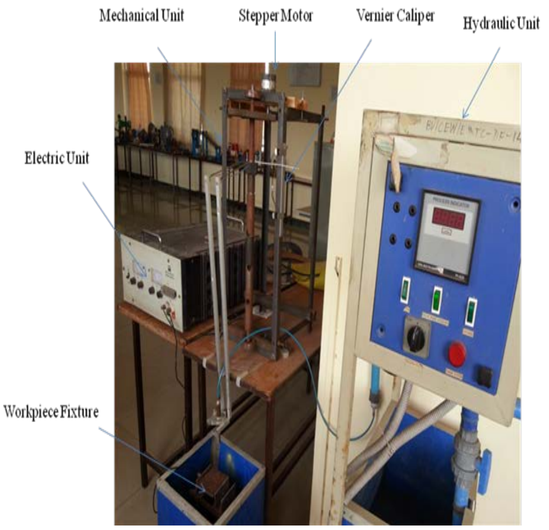


Fig. 2: ECM Set up

TABLE 4: L9 ORTHOGONAL ARRAYS WITH EXPERIMENTAL VALUES

| S.N. | Feed Rate | Electrolyte Flow Rate | Voltage |
|---|---|---|---|
| 1 | 0.5 | 150 | 12 |
| 2 | 0.5 | 250 | 14 |
| 3 | 0.5 | 350 | 16 |
| 4 | 0.7 | 150 | 14 |
| 5 | 0.7 | 250 | 16 |
| 6 | 0.7 | 350 | 12 |
| 7 | 1.0 | 150 | 16 |
| 8 | 1.0 | 250 | 12 |
| 9 | 1.0 | 350 | 14 |

Experimental material removal rate at different levels of parameters is given in table 5. From the table 5; large amount of material is removed at combination 1 mm/min feed rate, minimum electrolyte flow rate and maximum voltage. Tool feed rate and voltage are directly proportional to MRR and electrolyte flow rate is inversely proportional. As flow rate increases MRR decreases.

ANOVA and regression analysis has been done to validate the obtained results. Theoretical and experimental ANOVA and regression have been given in table 6 and table 7 respectively. From the ANOVA and Regression analysis it is clear that all the results are valid for the given parameter values and levels. To validate the results the values of R square and F (from table 6 and table 7) are considered at 95 % of confidence level. If the value of R square is 1 more accurate the results as well as higher the value of F more accurate the results.

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TABLE 5: EXPERIMENTAL MATERIAL REMOVAL RATE

| S. N . | Feed Rate | Electrolyte Flow Rate | Voltage | Material Removal Rate | | | |
|---|---|---|---|---|---|---|---|
| | | | | Initial Weight(g) | Final Weight(g) | mg / 5 min | mg/ min |
| 1 | 0.5 | 150 | 12 | 214.060 | 213.910 | 150 | 30 |
| 2 | 0.5 | 250 | 14 | 213.910 | 213.710 | 200 | 40 |
| 3 | 0.5 | 350 | 16 | 213.710 | 213.570 | 140 | 28 |
| 4 | 0.7 | 150 | 14 | 213.570 | 213.280 | 290 | 58 |
| 5 | 0.7 | 250 | 16 | 213.280 | 213.000 | 280 | 56 |
| 6 | 0.7 | 350 | 12 | 213.000 | 212.820 | 180 | 36 |
| 7 | **1.0** | **150** | **16** | **212.820** | **212.430** | **390** | **78** |
| 8 | 1.0 | 250 | 12 | 212.430 | 212.170 | 260 | 52 |
| 9 | 1.0 | 350 | 14 | 212.170 | 211.930 | 240 | 48 |

TABLE 6: THEORETICAL ANOVA AND REGRESSION ANALYSIS

| **Regression Statistics** | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.995775688 | | | | |
| R Square | **0.991569221** | | | | |
| Adjusted R Square | 0.986510754 | | | | |
| Standard Error | 0.026791375 | | | | |
| Observations | 9 | | | | |
| **ANOVA** | | | | | |
| | df | SS | MS | F | Significance F |
| Regression | 3 | 0.4221 | 0.1407 | **196.0217** | 1.32552E-05 |
| Residual | 5 | 0.003589 | 0.000718 | | |
| Total | 8 | 0.425689 | | | |

TABLE 7: EXPERIMENTAL ANOVA AND REGRESSION ANALYSIS

| **Regression Statistics** | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.951936074 | | | | |
| R Square | **0.906182288** | | | | |
| Adjusted R Square | 0.849891661 | | | | |
| Standard Error | 6.138175053 | | | | |
| Observations | 9 | | | | |
| **ANOVA** | | | | | |
| | df | SS | MS | F | Significance F |
| Regression | 3 | 1819.614 | 606.538 | **16.09828** | 0.005304633 |
| Residual | 5 | 188.386 | 37.67719 | | |
| Total | 8 | 2008 | | | |

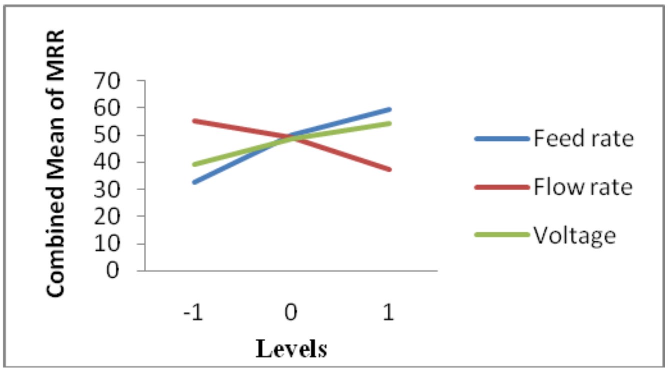


Fig.3: Combined effect of parameter (experimental)

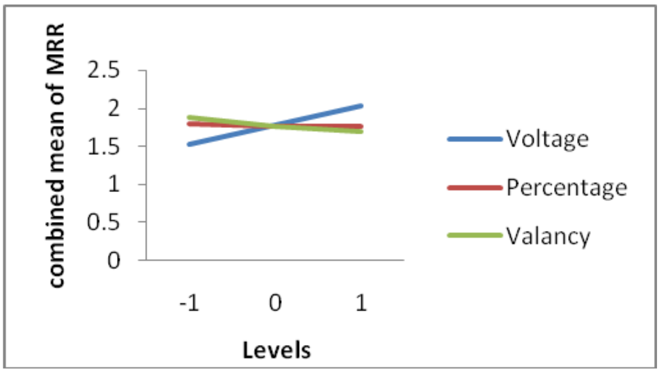


Fig.4: Combined effect of parameter (theoretical)

## IV. CONCLUSION

In electrochemical machining process material removal rate is calculated by means of Faraday's laws of electrolysis. While calculating MRR the process parameters such as tool feed rate, electrolyte concentration, electrolyte flow rate etc. are not considered. Only one parameter i.e. current has been taken into consideration. Experimentally material removal rate is calculated by measuring the weight of workpiece before and after machining as difference. For conducting experiments numbers of parameters are combined instead of considering each parameter separately by means Taguchi methodology. To validate the theoretical as well as experimental results ANOVA and Regression analysis has been performed. From ANOVA and Regression analysis it is concluded that the selected parameters are giving desired results. For that purpose values of R square and F are considered. Large values R square and F are desirable and are obtained. Main effect graphs are plotted to check interrelation of parameters and it is found that all the parameters are interrelated and affects each other as each line is crossing through other two lines.

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